Coupled Mesoscale Modeling of the Atmosphere and the Ocean

Richard M. Hodur, Julie Pullen[1], Xiaodong Hong, James A. Cummings[2], and James D. Doyle

Naval Research Laboratory
Monterey, CA 93943-5502

[1]Consortium for Oceanographic Research and Education (CORE) Postdoctoral Fellowship Program
Naval Research Laboratory
Monterey, CA 93943-5502

[2]Naval Research Laboratory
Stennis Space Center, MS 39529-5000

Abstract

The Naval Research Laboratory (NRL) is addressing the need for describing the coastal atmosphere-ocean environment through the development of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS). The atmospheric components of this system have been designed for effective use in the coastal zone, where many military operations take place and are often affected by adverse weather phenomena associated with these regions. The atmospheric components of COAMPS include a 3-dimensional multivariate optimum interpolation (3D MVOI) analysis system that can routinely ingest in-situ and remotely-sensed data and subject it to stringent quality control, producing analyses of the current conditions; and a forecast model, based on the nonhydrostatic formulation of the primitive equations that evolves these initial conditions to a user-specified time. The ocean component of COAMPS also features a 3D MVOI analysis that can assimilate in-situ and remotely-sensed observations, as well as incorporate subsurface thermohaline structure through the use of the Modular Ocean Data Assimilation System (MODAS) synthetic database; and the NRL Coastal Ocean Model (NCOM), designed for mesoscale ocean applications. This study is made up of three tasks. These are: (1) to produce unique, state-of-the-art, high-resolution, long-term atmospheric fields for NCOM forcing, (2) to test and evaluate methodologies for optimum coupling of mesoscale atmosphere and ocean models, and use these methodologies to study specific dynamic and physical atmosphere, ocean, and atmosphere-ocean processes, and (3) to use COAMPS coupled to the Wave Model (WAM) to study atmosphere-wave interactions. The production of COAMPS reanalyses have demonstrated the need for high spatial and temporal atmospheric fields to adequately describe the complex atmospheric phenomena that forces much of the observed structure of the ocean in ocean models. The use of these fields has enabled us to study ocean dynamic and thermodynamic processes in the Mediterranean Sea. Finally, we have coupled COAMPS to WAM and have shown that, for a limited sample of cases, air-wave coupling has the potential for improved wave forecasts and improved central pressure of tropical cyclones.

Introduction

The U. S. Navy has a need for the analysis and prediction of the atmosphere and the ocean. Routine military exercises can be profoundly affected by variations in the atmospheric temperature, relative humidity, and wind; and by variations in the ocean temperature, salinity, and currents. These variations can significantly affect tactical parameters, such as radar propagation, acoustics, and visibility, which can be critical to the success of military missions. Often, these variations occur across small spatial and time scales, making them difficult to observe and to predict.

The most consistent method to obtain analyses and prediction of the atmosphere and ocean is through the use of data assimilation systems that rely on sophisticated data quality control and analysis methods, and numerical prediction models. The use of such systems allows for the merging of observations from many different in-situ and remotely-sensed sources with a background field provided by a numerical model, into a 3-dimensional description of the state of the atmosphere and/or ocean. The observations provide information about the current conditions while the background field provides information from observations taken at previous times by projecting them forward to the current analysis time. This process is important in order to maintain spatial and temporal consistency, and to allow for the history of previous observations to be maintained in future analyses. In so doing, the model is allowed to generate useful information in data-void regions, based on the interpolation of the observations from adjacent areas and in relying on the dynamics and physics of the model to project this data forward in space and time. The performance of each of the components of the data assimilation system is critical to the overall performance of the entire system. The errors in the observations, in the analysis methods, and in the forecast model determine the quality of the final analyses.

Stand-alone data assimilation systems have been developed for the atmosphere and ocean. However, there is increasing evidence that suggests that the atmosphere and ocean data assimilation systems should be combined. It is clear that the atmosphere has profound impacts on the ocean. The atmosphere acts as the upper boundary condition for the ocean, and the surface atmospheric winds, temperature, precipitation, and radiation flux all play a strong role in forming and modulating the ocean circulation and thermohaline structure. There is mounting evidence that interaction with the ocean modifies the overlying atmosphere in important ways, as well. For example, recently Samelson et al. (2001) found that during coastal upwelling, the surface atmospheric temperature was cooled by 1-5 degrees on a 12-24 hour timescale by contact with the cooler ocean waters upwelled from depth. Also, Chelton et al. (2001) reported evidence of significant alterations in the observed equatorial surface wind stress field due to coupling between the atmospheric boundary layer and the underlying sea surface temperature. To fully account for these observed interactions as well as to anticipate the discovery of a host of other ways in which the ocean and atmosphere modify each other, NRL has undertaken the building of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS; Hodur 1997). The goal of this modeling project is to gain predictive skill in simulating the ocean and atmosphere at high resolution on time-scales of hours to a several days. Significant questions exist as to how tightly coupled the atmosphere and ocean data assimilation systems must be, and over what types of atmospheric and ocean conditions this coupling is important.

COAMPS Description

Atmospheric Component

While COAMPS represents an air-ocean coupled system, until recently much of the work focused on the development, testing, and the operational implementation of the four principal components of the COAMPS atmospheric data assimilation system. The first component is the quality control of observations, in which observational data from many sources (e.g., radiosondes, aircraft, satellite, ships) are screened for errors, redundancy, consistency with the previous forecast, etc. (Baker 1992). The second component is the analysis, in which the irregularly-spaced, quality controlled data are interpolated to the model's regularly-spaced grid. The interpolation method used by COAMPS is based on the multivariate optimum interpolation method (MVOI; Lorenc 1986). In the third component, model initialization, the analyzed fields are adjusted to conform to one of more dynamic and/or physical constraints. Finally, the fourth component is the numerical model, which integrates the initialized fields forward in time to a specified future time, using some approximate formulation of the primitive equations.

A great deal of flexibility has been built into COAMPS. First, the COAMPS grid can be set to any domain size and grid spacing at runtime, within the constraints of the computer system being used. Second, the grid can be located anywhere over the world, using one of 5 different map projections: polar stereographic, Mercator, Lambert conformal, spherical, or cartesian. Third, the system can be initialized with real- or idealized-data. Fourth, the model uses nested grids. The grid spacing is reduced by a factor of 3 between each nest. In this manner, the COAMPS grid can telescope down to resolutions of less than 10 km for areas in which high resolution is a necessity. Any number of nests can be defined at runtime. Fifth, a variety of lateral boundary conditions are available, supporting both real- and idealized-data experiments. Sixth, a single configuration managed version of COAMPS is used for all applications.

The atmospheric forecast model in COAMPS uses the nonhydrostatic form of the primitive equations as described in Klemp and Wilhelmson (1978). The nonhydrostatic form of the equations is necessary for modeling systems using a horizontal resolution less than approximately 10 km. For these resolutions, the vertical acceleration may become important, such as in convective systems or strong flow around steep topography. The COAMPS equations are solved on a staggered C-grid. COAMPS contains an advanced moist physics parameterization (Rutledge and Hobbs 1983), which is used in lieu of convective parameterization below 10 km grid spacing. This moist physics parameterization contains explicit equations for water vapor, cloud droplets, raindrops, ice crystals, and snowflakes. In addition, the COAMPS atmospheric model uses state of the art parameterizations for boundary layer processes and radiation.

The atmospheric portion of COAMPS has been operational at FNMOC since June 1998, and is currently run operationally over seven separate areas. This includes areas that cover the Mediterranean Sea, portions of Asia, and the coasts of North America. Some of the areas utilize triply-nested grids with resolutions of 81, 27, and 9 km, while the remainder of the areas utilize a doubly-nested grid configuration using resolutions of 81 and 27 km. All COAMPS areas currently use 30 vertical levels, with the model top at approximately 34 km. The length of the

COAMPS forecast varies based on the area and the nest. The longest forecasts extend to 72 h for 81 and 27 km grids, while the shortest forecasts (the 9 km grids) extend only to 24 h.

Ocean Component

The ocean analysis component of COAMPS is a fully 3-dimensional oceanographic implementation of the multivariate optimum interpolation algorithm that is used in the COAMPS atmospheric analysis component. The theoretical basis of the multivariate method is described in Lorenc (1981) and Daley (1991). The ocean analysis variables are temperature, salinity, geopotential, and the u-v velocity components. Geopotential observations are calculated from observations of temperature and salinity assuming a level of no motion. The multivariate correlations compute geostrophically balanced increments of velocity from the analyzed increments of geopotential. In this way, adjustments to the ocean's mass field are correlated with adjustments to the ocean's flow field. The geostrophic coupling is relaxed near the equator and in shallow water where friction terms dominate the flow. The COAMPS ocean analysis component is executed in a sequential incremental update cycle, and a short-term model forecast (or previous analysis) provides the analysis background field.

All observational data are subject to quality control (QC) procedures prior to assimilation. The primary purpose of the QC system is to identify observations that are obviously in error, as well as the more difficult process of identifying measurements that fall within valid and reasonable ranges, but are erroneous. A secondary use of the QC system is the creation and maintenance of an analysis-forecast increment database for use in the *a posteriori* computation of the optimum interpolation statistical parameters. QC procedures common to all data types include land/sea boundary checks and background field checks (previous analysis, forecast, climatology). QC procedures unique to different data types include; location (speed) test for drifting buoy and surface ship observations; instrumentation error checks for expendable bathythermographs (XBTs) and profiling PALACE floats; sensor drift for fixed and drifting buoys; and large-scale bias detection for satellite retrievals of SST. The need for quality control is fundamental in the analysis system; erroneous data can cause an incorrect analysis, while rejecting extreme data can miss important events. The decisions made at the quality control step are likely to affect the success or failure of the entire analysis/forecast system.

The COAMPS ocean analysis can also be used to construct 2D ocean fields of sea surface temperature (SST) and sea ice concentration. These 2D fields are used as the lower boundary conditions in the atmospheric forecast model. SST analyses are created using both satellite SST retrievals and *in situ* measures of SST from surface ship and fixed and drifting buoy data. Sea ice concentration is analyzed using DMSP SSM/I retrievals of ice concentration. SST and sea ice are analyzed simultaneously and are cross validated by (1) setting positive sea ice concentration retrievals to 0% ice when SST exceeds 1 C, and (2) inserting supplemental SST observations at the freezing point of sea water into the analysis when sea ice concentration exceeds 55%.

The greatest difficulty of any eddy resolving ocean data assimilation system is the lack of synoptic real-time data at depth. On a global basis the daily accumulation of XBT data routinely available is approximately 250 reports. Virtually no salinity observations are available in real-time. To supplement the sparse subsurface observational data, the COAMPS ocean analysis system generates temperature and salinity profiles from the Modular Ocean Data Assimilation System (MODAS) synthetic database. The MODAS database contains coefficients that can be used to infer subsurface temperature structure from satellite altimeter sea surface height (SSH) observations and analyzed SST. Salinity is then computed from temperature using climatologically based temperature-salinity relationships. The synthetic profiles are appended to the real-time observations and assimilated in the same way as any other observation, but with unique error characteristics specified. The errors of the synthetic profiles are dependent both on the accuracy of the SST and SSH predictor fields and on the magnitude of the correlation of the subsurface temperature structure to SST and SSH. The synthetic profile errors vary in both space and time.

The COAMPS ocean analysis system supports a variety of map projections (Mercator, Lambert Conformal, Polar Stereographic, Spherical) and can be run on a nested grid structure at various grid resolutions producing multi-scale analyses. The update cycle of the COAMPS ocean analysis can be set independently of the atmospheric analysis update cycle, and post-time analyses can be run to process delayed-mode observations. Timely receipt of ocean observations is an important issue for a real-time system, and particularly so when the ocean forecast model is run in coupled mode with the atmospheric forecast model. The COAMPS ocean analysis system has been designed to handle the inevitable delays in the receiving and processing of observations at the production center.

The COAMPS ocean model is the Navy Coastal Ocean Model (NCOM) developed by Martin (2000). NCOM is designed to offer the user a range of numerical choices in terms of parameterizations, numerical differencing, and vertical grid structure. NCOM is based on the hydrostatic primitive equations, and has prognostic variables for the ocean currents, temperature, salinity, and surface height. An implicit formulation is used for the barotropic component. The equations are solved on the staggered C grid. One special aspect of NCOM is that it uses a hybrid vertical coordinate system. In this system, one can use all sigma-levels, all z-levels, or a combination of the sigma-levels for the upper ocean and z-levels below. Advection can be treated with second-order centered, or third-order upwind finite differencing. Options for boundary layer mixing include Mellor-Yamada 2.0 and Mellor-Yamada 2.5 schemes. The model also includes options for treating open boundaries using radiation conditions that have been successful in numerical models in the past.

A flux coupler has been developed to couple the COAMPS atmosphere and ocean models through the exchange of surface fluxes of heat, momentum, moisture, and radiation across the air-water interface, as well as to include the effects of precipitation falling into the ocean. Since the atmospheric and ocean models are expected to have different resolutions for many applications (and perhaps different grid projections, as well), the flux coupler has been designed to interpolate fields between the atmospheric and ocean grids to account for this differences. Special care is taken to ensure consistency of the forcing fields at the land/sea boundary.

Results

Atmospheric Reanalyses

The success of an ocean model forecast is limited by the accuracy of the surface flux and surface stress fields supplied by the atmospheric model. Unfortunately, these atmospheric fields are often characterized by features with relatively small spatial and temporal scales. This is most pronounced near coastlines, where strong diurnal temperature oscillations can cause rapid wind changes and where interactions of the wind with steep topography can force strong local wind patterns. This implies that the atmospheric forcing must come from high-resolution analyses and/or forecasts that can resolve such features. In this project, we are generating high spatial and temporal resolution fields to force the COAMPS ocean model by running the COAMPS atmospheric data assimilation system for extended time periods over regions of interest. We are currently focusing on four different areas for our atmospheric reanalyses: the Mediterranean Sea, the eastern Pacific, the Baltic Sea, and the Adriatic Sea. Details of these areas are presented in Table 1. Note that two different sets of reanalyses are being done over the Mediterranean Sea, with the difference in the two runs being the horizontal resolutions of the grids.

The COAMPS reanalyses are all produced using a 12 hour incremental data assimilation cycle. The first analysis for each area uses the analysis fields valid at the starting time from the Navy Operational Global Atmospheric Prediction System (NOGAPS) for the first guess, and performs a 3D MVOI analysis using all available observations for that time. All subsequent analyses for that particular area use the 12 hour COAMPS forecast fields for each nest generated from the previous analysis time as the first guess fields. Also at each analysis time, a 2D OI analysis of the sea surface temperature (SST) is generated for each COAMPS grid nest. Following each analysis, a 24 hour forecast is generated for each nest. A sample of the SST analyses for the three nests over the eastern Pacific are shown in Fig. 1. During each forecast, selected fields (Table 2) are output on an hourly basis to serve as the upper boundary conditions for the COAMPS ocean model.

The significance of the resolution of COAMPS on the wind fields in an area such as the Mediterranean is seen in Fig. 2. The Mediterranean is typically dominated by many local winds (e.g., Mistral, Levante, Etesian). The Mistral is formed in the Gulf of Lion by the channeling of the flow between the Pyrennes on the border of France and Spain, and the Alps in northern Italy. Using an 81 km grid, the average wind for the month of November 1999 in the Gulf of Lion is approximately 5 m/s, while it is approximately 9 m/s in the 27 km grid. Independent verification of the Mistral for individual cases (not shown) indicates that the 27 km grid represents the maximum winds in the Mistral better than the 81 km grid. The strength of the Mistral and the other local wind regimes in the area around the Mediterranean, and the associated increase in surface stress, is expected to play a large role in the circulation and thermohaline structure of the Mediterranean Sea.

Air-Ocean Coupling: Ocean Spin-up

Our initial tests of air-ocean coupling with COAMPS is focused on the Mediterranean Sea. This body of water was chosen for a number of reasons. First, it is an area that routinely exhibits many small-scale features both in the atmosphere and in the ocean that require a high-resolution system such as COAMPS to adequately represent. Second, analyses and forecasts in the area around the Mediterranean Sea for both the atmosphere and ocean are very important for the missions that the U.S. Navy conducts in this area. Finally, the Mediterranean Sea is a nearly-enclosed basin, meaning it can be run without the requirement for global ocean fields for lateral boundary conditions.

Our first test with NCOM was to perform a multi-year spin-up over the Mediterranean Sea. This spin-up featured one-way coupling (i.e., the atmosphere forces the ocean) using the hourly fields from our COAMPS atmospheric reanalyses described above to force NCOM. For this experiment, NCOM used a horizontal resolution of 9 km and 31 vertical levels (15 sigma-levels at the top, 16 z-levels below). An inflow of 1.0 Sv was prescribed at the Strait of Gibraltar with a return flow of the same magnitude in the bottom-most layers. NCOM was integrated for over two years, using the COAMPS reanalysis fields from October 1998 through September 1999 for each year of the multi-year spin-up. After this time, it was assumed that the model reached a steady-state, based on the time series of the domain-averaged kinetic energy (Fig. 3). Our preliminary analysis is focused on the second year of this spin-up. Using the flux coupler with hourly COAMPS forcing, we were able to simulate many observed features of the general circulation of the Mediterranean Sea with NCOM, such as sub-basin scale gyres and intense coastal boundary currents.

The average mean surface height of the Mediterranean Sea generated from the second year of our spin-up run is shown in Fig. 4. Cyclonic motion dominates the northern part and anti-cyclonic motion dominates the southern part of the Mediterranean Sea. Two anticyclonic gyres are formed in the Alboran Sea with the eastern one constituting the Almeria-Oran front, which is a strong density gradient between the inflowing Atlantic water and the resident water of the Mediterranean. The prominent jet-like currents generated in the simulation include: the Algerian current flowing along the Algerian coast, the Atlantic Ionian Stream, the Mid-Mediterranean Jet, and the Asia minor current in the east. Our simulations also include cyclonic gyres (Lions, Tyrrhenian, Cretan, and Rhodes gyres) and the anticyclonic gyres (Pelops, Mersa-Matruh, and Shikmona gyres) that are consistent with observations made in the Mediterranean. In addition, we find evidence of three cyclonic gyres in the Adriatic Sea.

The mean surface elevation and geostrophic currents from the second year of the ocean spin-up for winter (Fig. 5a) and for summer (Fig. 5b) indicate significant differences across the Mediterranean Sea during the different seasons of the year. The western Mediterranean Sea is dominated by strong cyclonic motion during the winter season. During the summer, the circulation is smaller and weaker, with a number of transient gyres forming along the north African and western Italian coasts. The cyclonic circulation of the western Mediterranean in the winter is comprised of strong gyres in the Tyrrhenain Sea and the Gulf of Lion. These weaken and break up into smaller scales during summer. The Gulf of Lion gyre becomes stronger during winter by enhancement of winter convection. In the eastern Mediterranean Sea, the Ionian Stream and Mid-Mediterranean jet exhibit similar patterns for both the summer and winter seasons. However, the Mersa-Matruh gyre and Shikmona gyre are stronger in summer and weaker in winter. However, the circulation of the Rhodes gyre is stronger in the winter season, presumably strengthened convective processes. The cyclonic gyres in the Adriatic Sea are found in both the summer and winter seasons, with small changes in their strength between the seasons.

Air-Ocean Coupling: Data Assimilation

The ocean data assimilation system relies on a tight coupling between the MVOI and NCOM. To achieve this, both components share the same high-resolution bathymetry (i.e., dbdbv) and land/sea fields on a grid with the same horizontal and vertical dimensions. The system currently being tested for the Mediterranean Sea uses a 6 km horizontal resolution on a Lambert conformal grid projection and 40 vertical levels. In the ocean model, 15 vertical sigma levels are used in the upper 100 m, with z-levels below. The minimum ocean depth is set at 5 m.

In order to initialize the system, an MVOI analysis is generated from climatology using expanded data time windows. These "cold start" fields are interpolated from the MVOI z-levels to the sigma/z-levels of NCOM. A static stability test is performed, and temperature and salinity are adjusted to achieve neutral buoyancy, if required. NCOM is then run in a prognostic mode using the previous 5 days of forcing from the 27-km COAMPS. Following this cold start procedure, every subsequent analysis (at 12 hour intervals) uses the previous 12 h NCOM forecast temperature, salinity, and velocity fields as the first-guess fields for the current analysis. The analyzed temperature, salinity, and velocity increments are then interpolated to the NCOM vertical grid and added to 12 h forecast fields NCOM fields that are already on the model vertical grid. Following each analysis, at 12 hours intervals, a 4-day ocean forecast is produced.

When the forecast model is unconstrained by data assimilation, it can drift away from the expected circulation features on event timescales. Fig. 6a shows a 14 day NCOM spin-up forecast of the sea surface elevation initialized with the cold-start procedure described above. Fig. 6b shows a 12 hour NCOM forecast of the sea surface elevation valid at the same time, but while it used the same cold-start procedure as the forecast shown in Fig. 6a, it also used the 12 hour cycling procedure, as described above, during the subsequent 14 days. Significant differences are found in the intensity of many of the features in the Mediterranean Sea. We are just beginning to validate the fields with observations, and the preliminary results indicate that the cycling run better represents the circulation features at this time.

Air-Wave Modeling

The atmospheric portion of COAMPS has been coupled in an interactive mode to the 3rd generation (cycle 4) of the Wave Model (WAM) (WAMDI Group 1988). The coupling methodology follows Janssen (1991) and Doyle (1995) and includes the processes represented by mutual interaction of the wind waves and boundary-layer stress. The roughness length used in the coupled simulation is represented by,

$$z_o = \beta \frac{\tau}{g\rho(1-\tau_w/\tau)^{0.5}} \tag{1}$$

where τ is the total stress and τ_W is the wave-induced stress. The constant β is chosen as 0.01 implying that (1) reduces to the standard Charnock relationship. For a young windsea, the effective Charnock parameter can be enhanced by an order of magnitude. The simultaneous coupling is physically achieved through communicating the atmospheric stress to the wave model every WAM time step. An iterative technique is then used to calculate τ_W based on the 10-m wind speed, drag coefficient and τ.

A number of simulations of mesoscale phenomena that are modulated by air-sea interaction processes have been performed using the fully coupled COAMPS-WAM system including three major tropical cyclones and a topographically forced Bora event over the Mediterranean Sea. In these applications, the wave and atmospheric models were integrated simultaneously and on identical grids with horizontal grid increments ranging from 12 km to 5 km. One of the coupled simulations was focused on tropical cyclone Bonnie during an earlier phase of the tropical cyclone on 24 August. On this day, the sea surface directional wave spectrum was measured using the NASA airborne Scanning Radar Altimeter (SRA) carried aboard a NOAA WP-3D hurricane research aircraft at a height of 1.5 km (Wright 2000). The SRA derived significant wave height superimposed on the NOAA/AOML/HRD surface wind field analysis are shown in Fig. 7a (from Wright 2000). The maximum significant wave height derived from this composite analysis of 5 flight segments is 10.7 m and was located in the northeast quadrant of the tropical cyclone. The simulated significant wave heights for the uncoupled and coupled simulations of Bonnie are shown in Figs. 7b-c. The significant wave height maximum in the northeastern quadrant is considerably reduced in the coupled simulation, in spite of the dominance of the swell. The coupled simulation is in overall closer agreement with the SRA derived wave field than the uncoupled case.

The other simulations of tropical cyclones indicate that the impact of wave-induced stress was largest for the most intense of the three tropical cyclones, Mitch. The central pressure in the coupled simulation in this particular case was 8 hPa more intense than the uncoupled simulation due to larger surface heat flux effects. Significant wave height maxima were typically ~15% lower in the coupled simulations. Overall, the results suggest that in order to accurately simulate the air-sea interface, a coupled atmosphere/ocean wave model system is needed, in particular for extreme events.

Conclusion

The Naval Research Laboratory is developing and testing an ocean data assimilation component of COAMPS. The ocean component includes data quality control, 3-dimensional analysis capability through the multivariate optimum interpolation technique, and prediction capability through a hydrostatic, free-surface ocean model. The COAMPS ocean model is coupled to the COAMPS atmospheric model through a generalized flux coupler. The flux coupler allows for different grid projections and different grid resolutions between the atmospheric and ocean grids. In addition, COAMPS has been coupled to a wave model.

It is critical that analyses and predictions of the ocean be forced with high-resolution atmospheric fields in order to develop the proper structures in the ocean. In this project, we are generating high-resolution fields with the atmospheric data assimilation of COAMPS for four areas of the world using resolutions as high as 4 km. These fields serve as a baseline for the validation of the atmospheric component of COAMPS. It is important to establish this capability in order to measure the impact of adding ocean coupling to the atmospheric forecasts. The reanalysis fields also are used for input to the COAMPS ocean model in our one-way coupled tests, and demonstrate the importance of high-resolution modeling in coastal areas and areas dominated by significant topographic features. Our reanalyses validate the skill of COAMPS, demonstrate the need to use proper data assimilation methods to retain information from observations taken at previous times, and demonstrate the need to use unfiltered model output on the native model grid for forcing ocean models. We will continue our reanalyses for the areas we have been working on and expand to other areas.

Within our air-ocean coupling work, we are testing the abilities of the ocean component of COAMPS in two ways over the Mediterranean Sea. First, we are performing long-term spin-up solutions of the ocean by forcing the ocean model with COAMPS fields from our reanalyses. We have demonstrated that we can simulate many of the features of the Mediterranean. Our next test will be to study the impact of changing the temporal and spatial resolutions of this forcing to determine the sensitivity of the ocean model to atmospheric changes. Second, we are testing a complete ocean data assimilation system, similar to many data assimilation systems used for atmospheric applications that are in operational use around the world. This system allows for the routine ingest of data (e.g., buoy, XBT, satellite, ship, etc.) at a fixed interval (usually 12 hours) through the 3-dimensional multivariate optimum interpolation technique. The analysis constructed by merging all current observations with the model forecast from the previous analysis time is then used for the initial conditions for the current forecast. This study has demonstrated that the use of this data assimilation technique is a powerful tool for combining the forecast skill of the ocean model with advanced analysis methods to construct accurate analysis and forecast ocean fields. We will continue to validate the predictive skill of the COAMPS ocean model and refine the methods we have for ocean data assimilation.

Finally, we have coupled the COAMPS atmospheric model to the wave model, WAM. We have shown that we can improve predictions of wave heights with the air-wave coupled system for a limited number of cases. In addition, COAMPS-WAM was able to successfully model the wave spectra for a tropical cyclone.

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Tables

Area	Resolutions (km)	Start Date	Through
Mediterranean Sea	81/27	1 Oct 98	30 Sept 00
Mediterranean Sea	36/12	1 Oct 99	30 Nov 99
Eastern Pacific	81/27/9	1 Oct 98	30 Sept 00
Baltic Sea	81/27/9	1 Nov 99	31 Jan 00
Adriatic Sea	36/12/4	1 Oct 00	30 Nov 00

Table 1. COAMPS reanalysis areas, resolutions of grids, starting date of reanalyses, and ending date that reanalyses have been run through.

Field	Level
Pressure	Mean sea level
u-component of wind	10 m
v-component of wind	10 m
Air temperature	2 m
Relative humidity	2 m
Total precipitation	Surface
Sensible heat flux	Surface
Latent heat flux	Surface
Total radiative flux	Surface
Solar radiative flux	Surface
Total wind stress	Surface
u-component of stress	Surface
v-component of stress	Surface

Table 2. List of COAMPS fields and associated levels output hourly for each reanalysis area.

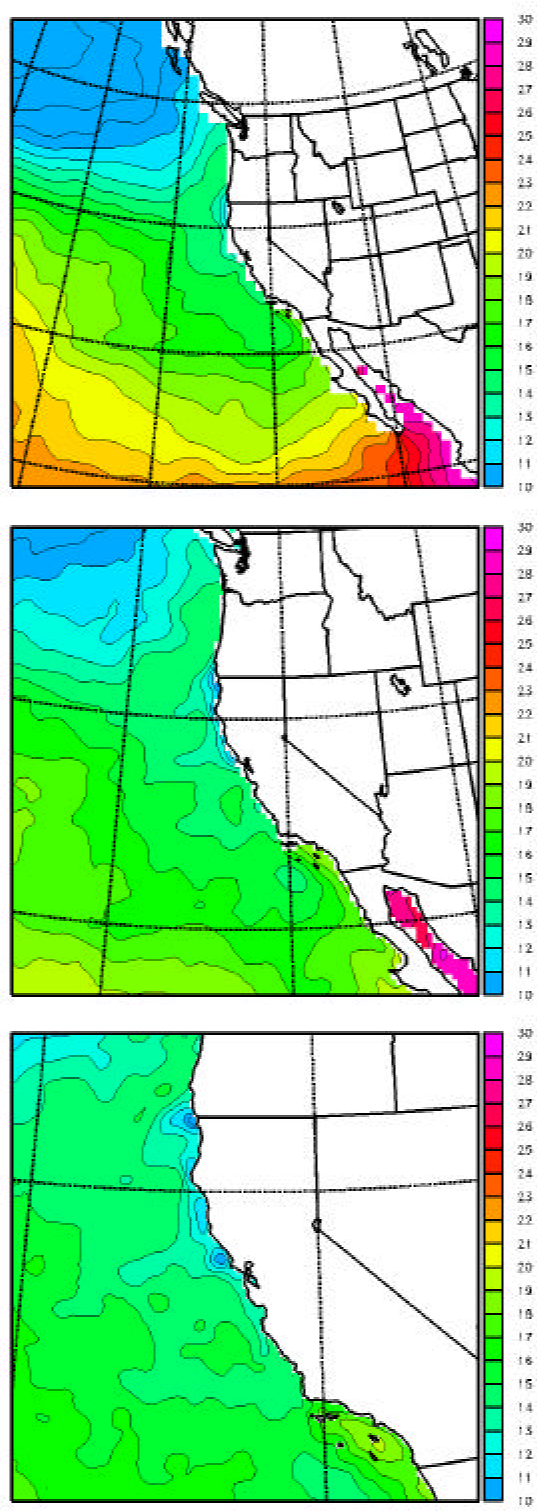
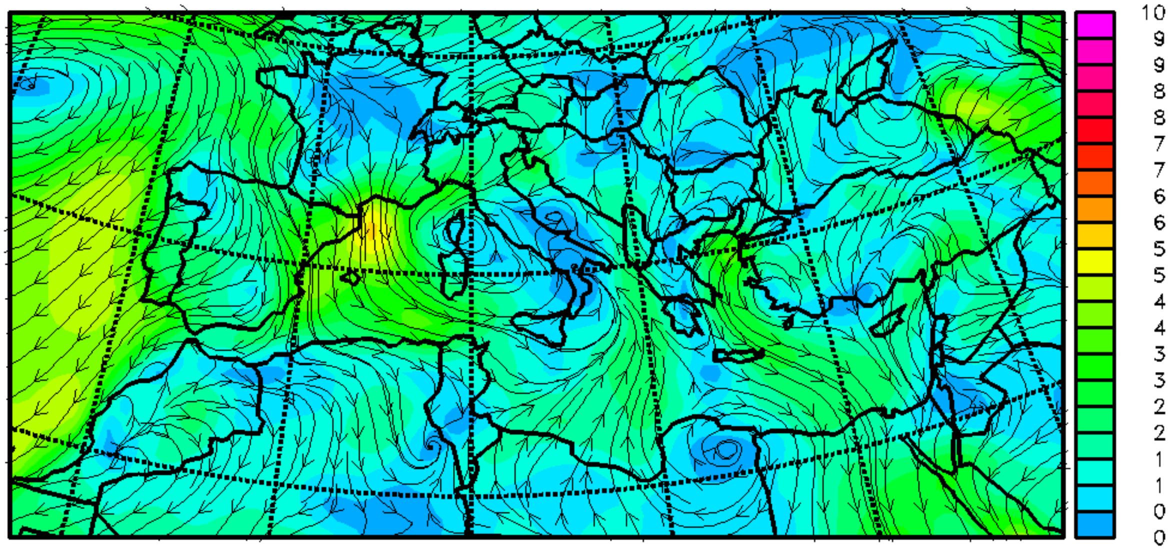
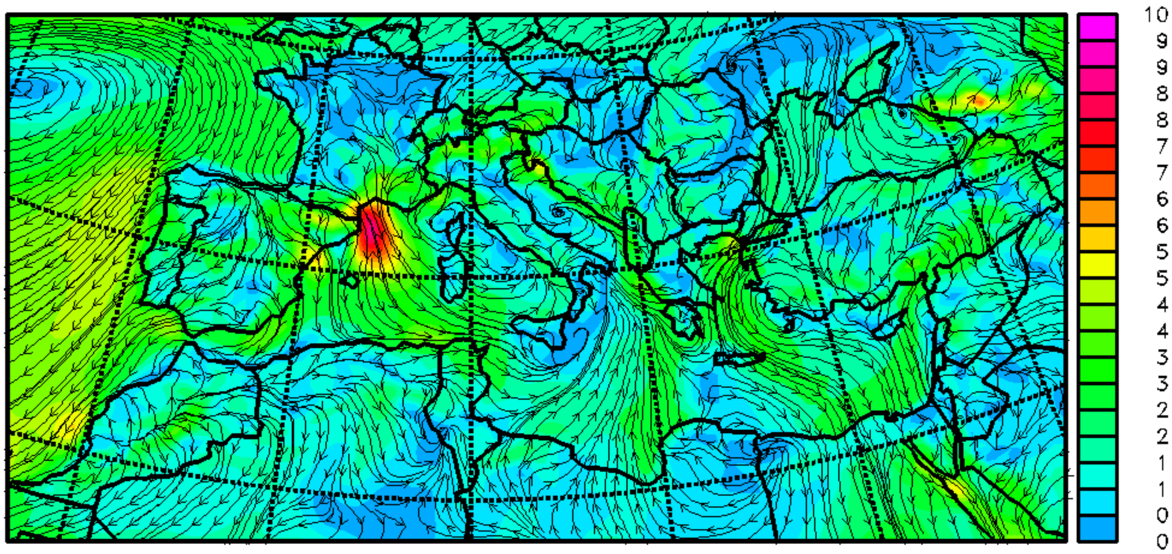


Fig. 1. COAMPS sea surface temperature analyses using 2-dimensional optimum interpolation analysis at 0000 UTC 1 July 1999 for (a) 81 km grid, (b) 27 km nest, and (c) 9 km nest.



(a)



(b)

Fig. 2. Average 10 m wind speed (m/s) and streamlines from COAMPS reanalyses over the Mediterranean area for November 1999 for (a) 81 km grid, and (b) 27 km grid. Winds are averaged for forecast times of 1-12 hours, in hourly intervals. In (a), only that portion of the 81 km grid that is contiguous with the 27 km grid is shown.

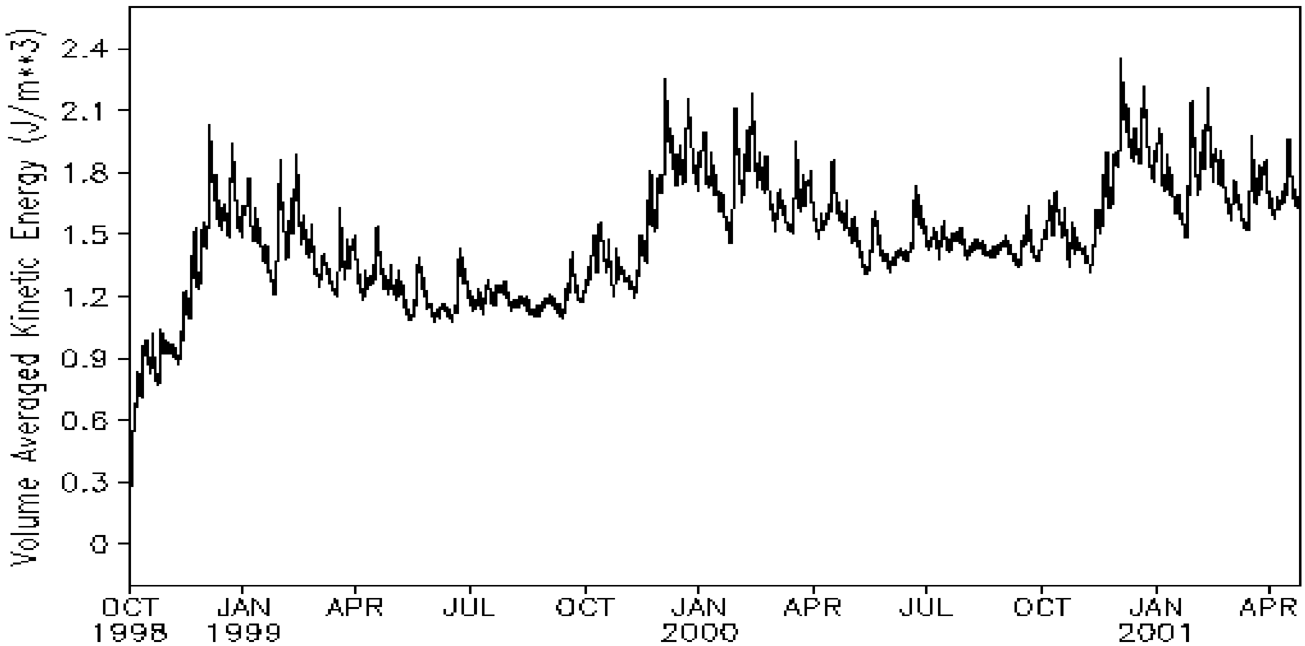


Fig. 3. Volume averaged kinetic energy for NCOM spin-up.

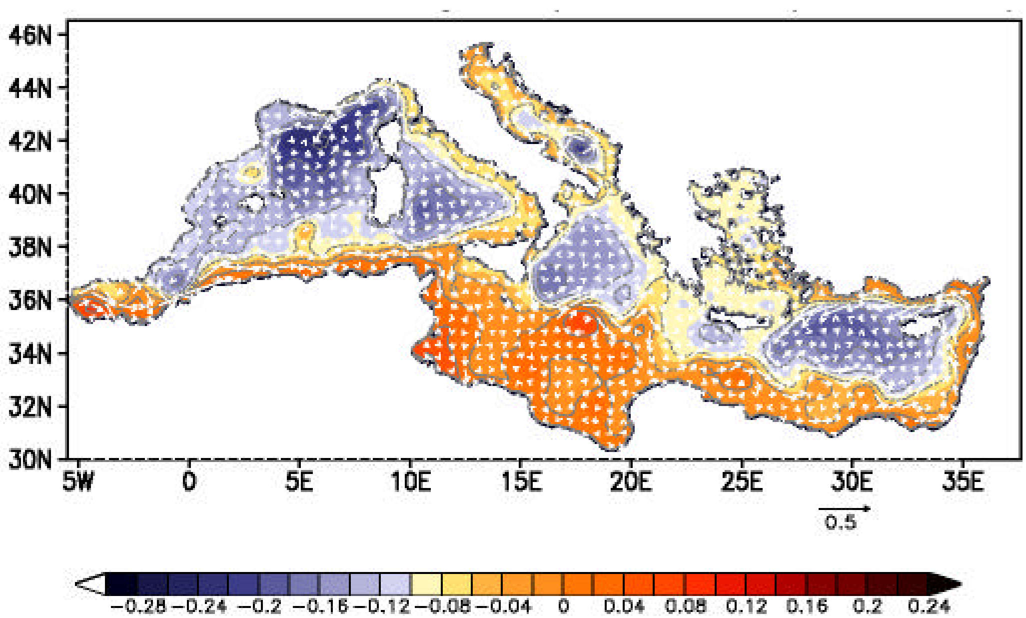
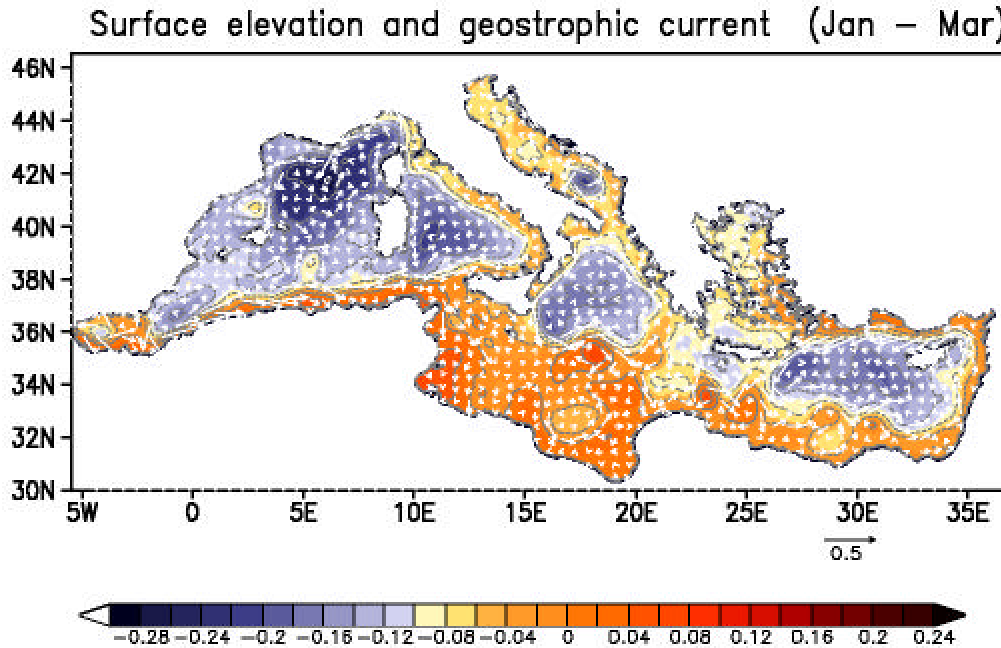
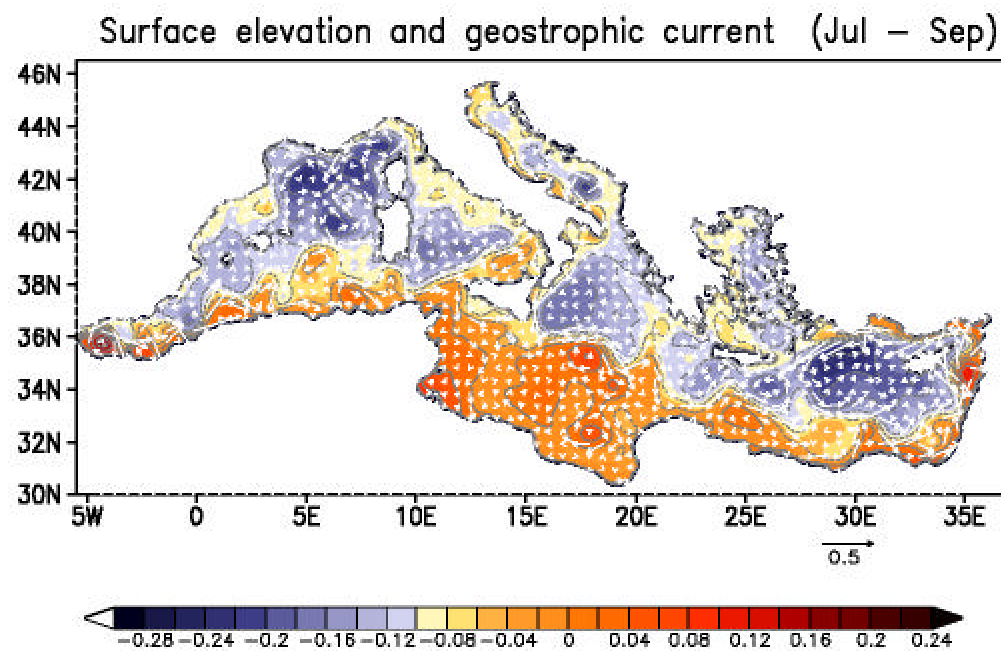


Fig. 4. Annual mean surface elevation (cm) and geostrophic currents for the second year of NCOM spin-up.



(a)



(b)

Fig. 5. Surface elevation and geostrophic current (a) for winter and (b) for summer from second year of NCOM spin-up.

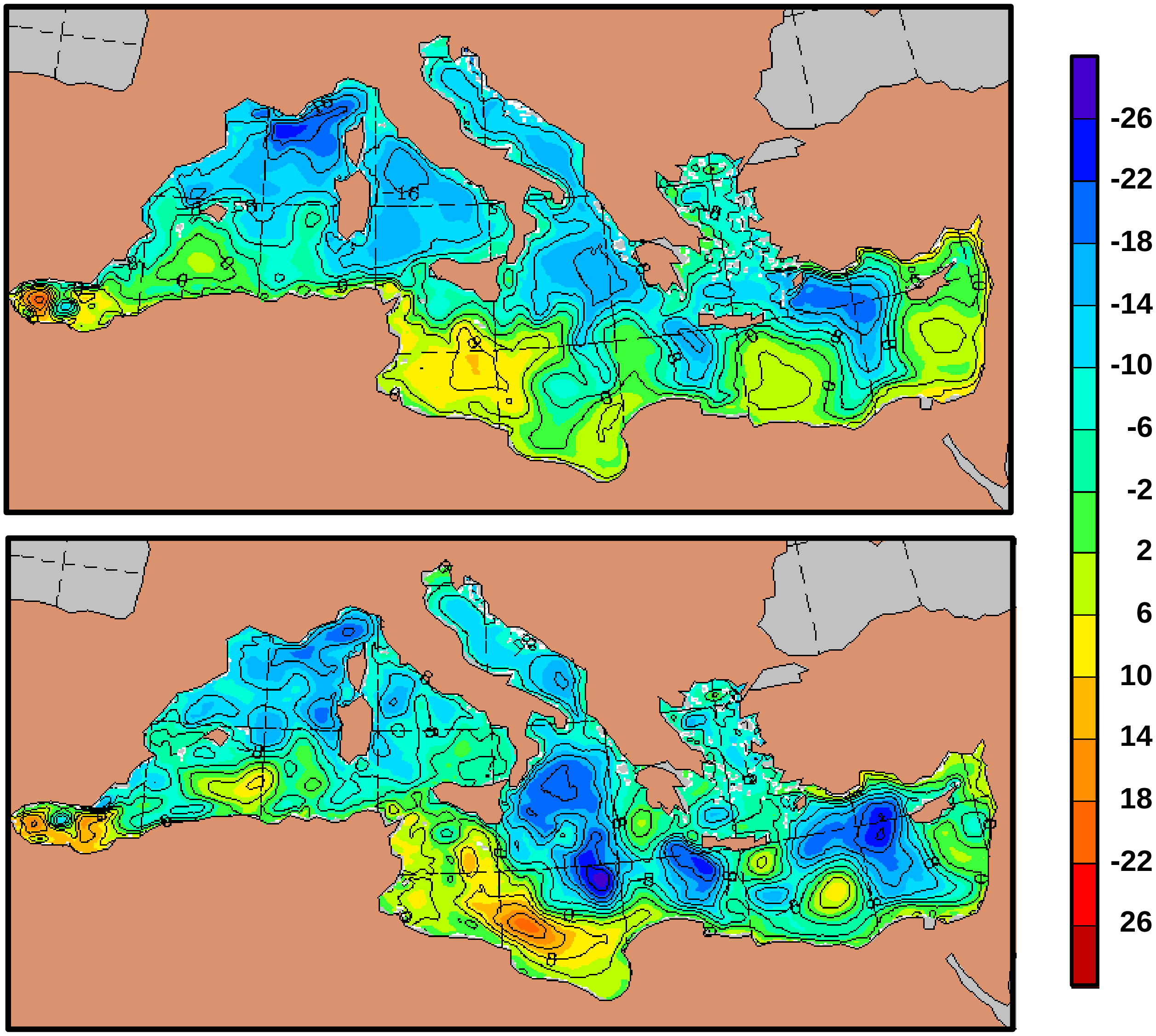


Fig. 6. NCOM forecasts of sea surface elevation (cm) from (a) 14 day spin-up run and (b) 12 hour forecast from a 14 day cycling run using a 12 hour incremental data assimilation cycle.

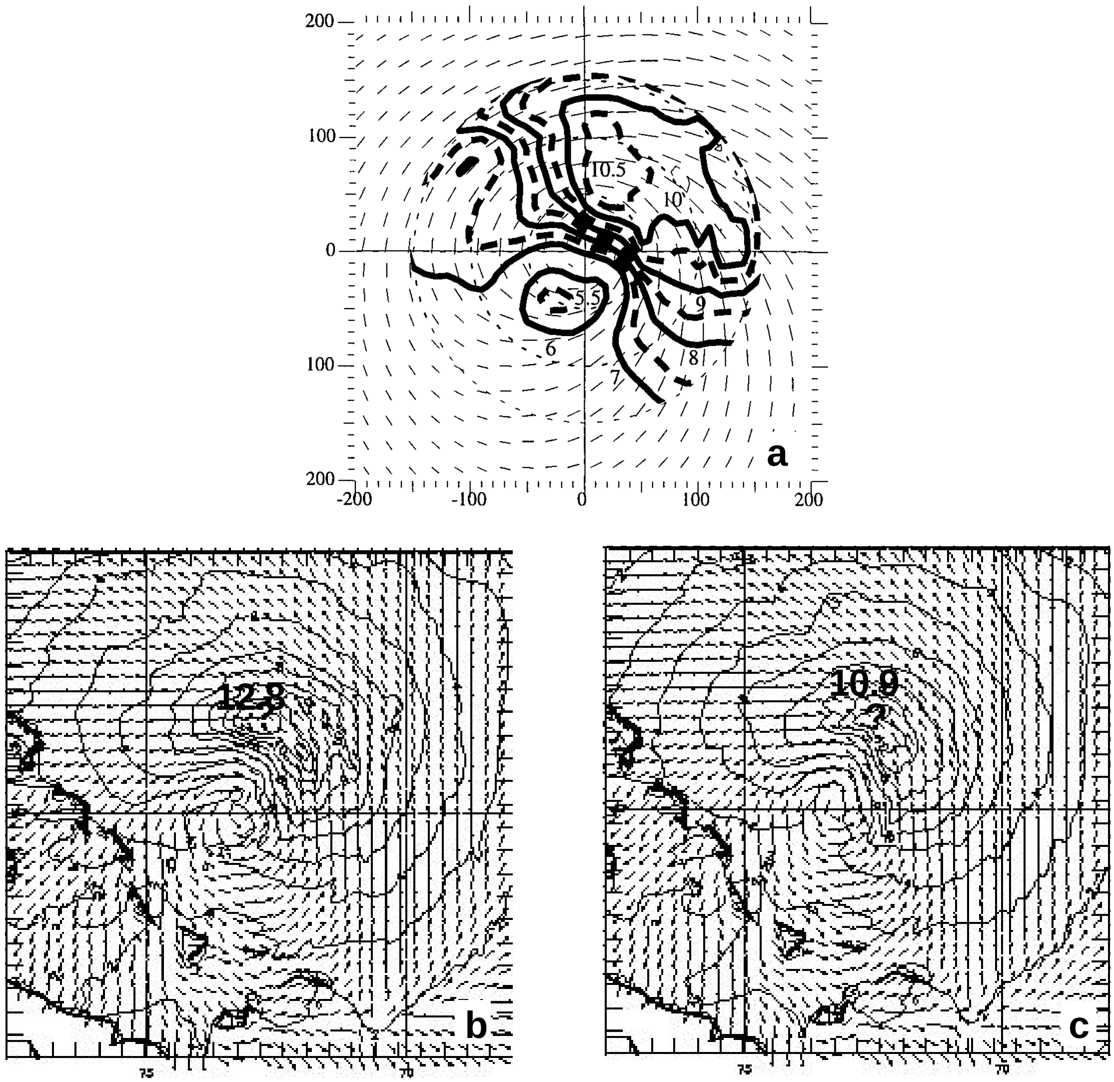


Fig. 7. NASA airborne Scanning Radar Altimeter derived significant wave height (m) based on NOAA WP-3D research aircraft data from hurricane Bonnie on 24 August 1998 (from Wright 2000) (a). Fig. 4. Simulated significant wave height (m) for the (b) uncoupled and (c) coupled simulations for 1200 UTC 24 August 1998 (24 h).